# On-orbit validation of the geolocation accuracy of GOES-16 Geostationary Lightning Mapper (GLM) flashes using ground-based laser beacons

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# Geostationary Lightning Mapper (GLM)

The GLM data shown in this presentation

# Geostationary Lightning Mapper (GLM)

New Instrument on GOES-R Series Satellites

Natural Hazards and Lightning

- Tornadoes
- Hailstorms
- Wind
- Thunderstorms
- Floods
- Hurricanes
- Volcanoes
- Forest Fires
- Air Quality/NOx

# GLM Overview

Spaceborne Instrument parameters

Staring sensor with truncated $8^{o}$ radius circular FOV

At nadir 30x30 $\mu$m pixel has 8x8 km footprint

Pixel pitch decreases with increasing field angle to minimize footprint growth

1372x1300 pixel array, single spectral band: $\lambda$ = 777.4 nm $\Delta\lambda$ = 1 nm

503 Hz frame rate

Onboard processing (Real Time Event Processor [RTEP])

Signal in each pixel compared to background (average of previous signals in same pixel)

Event detected when Pixel Signal > Threshold + Background

Background saved every 2.5 minutes and used for image navigation

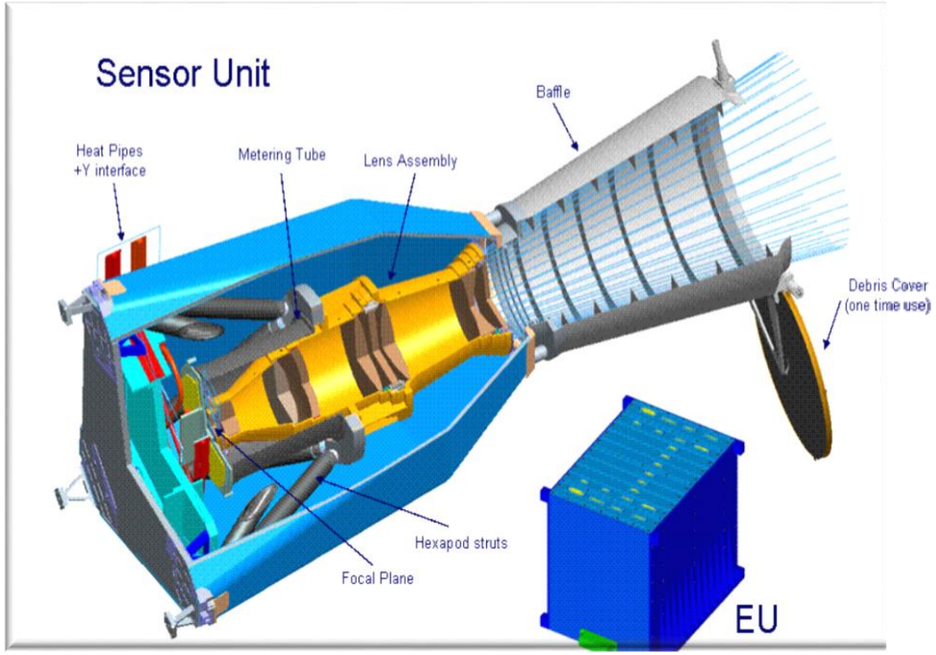
Ground processing

Lightning flash declared when 2+ spatially overlapping groups are detected within 1/3 sec

Flashes at same frame time & adjacent pixels grouped

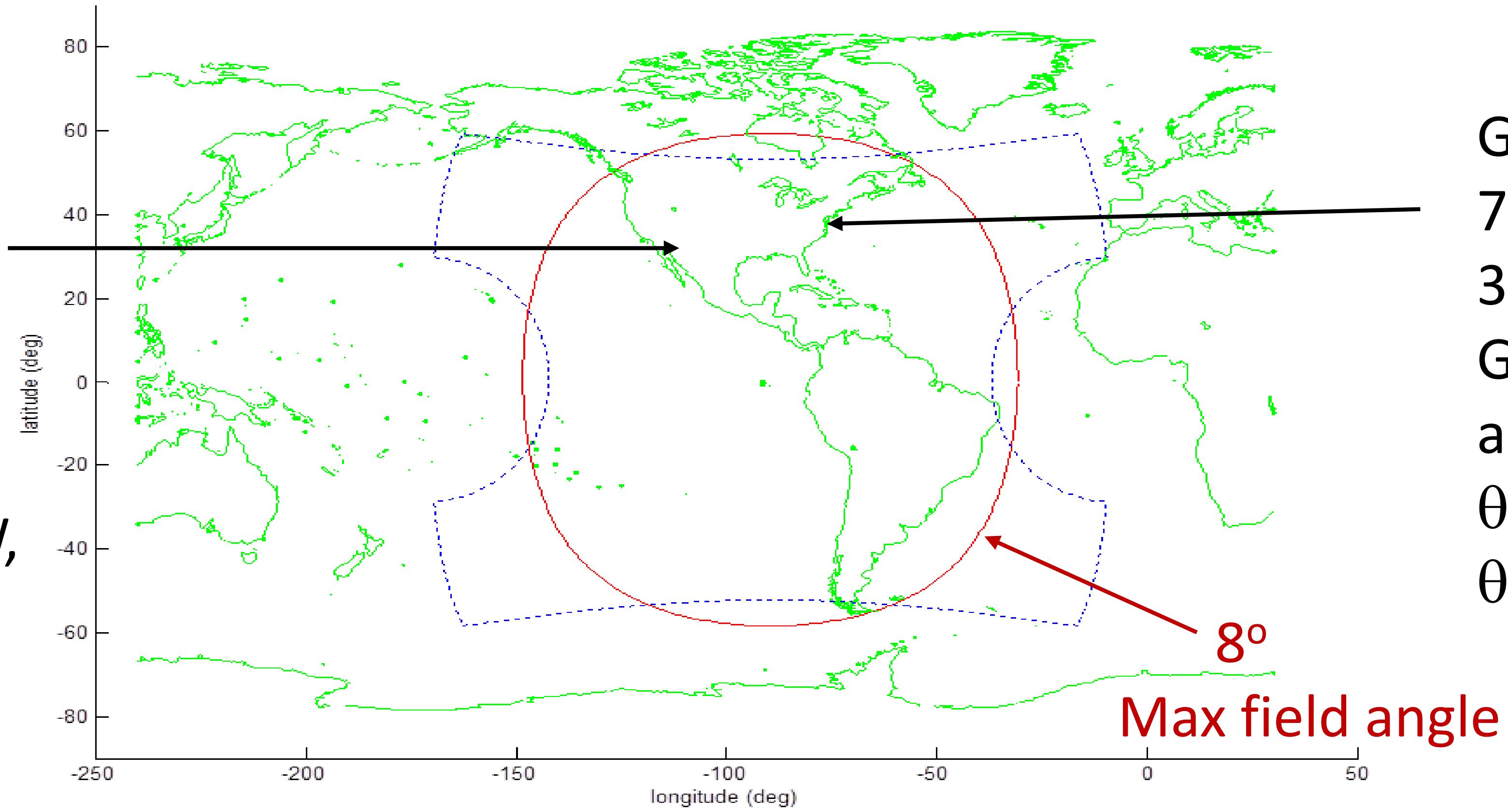
SW filters eliminate cosmic ray streaks, contrast leakage, sun glints, etc.

Can detect lightning against 100x brighter cloud background



# GLM's Coverage from GEO @ 89.5° W
## (intersection of 2 curves)

Mon. Pk.
116.4° W
32.8° N
GLM field angle
$\theta_x$ = 3.72° W,
$\theta_y$ = 5.26° N




GSFC
76.5° W
39.0° N
GLM Field angle
$\theta_x$ = 1.67° E,
$\theta_y$ = 6.11° N

Using MOBLAS sites within the USA minimizes cost & requirements (e.g. ITAR)

# Optical Lightning Detection: How it works

***Lightning from Space:*** Lightning appears like a pool of light on the top of the cloud as the discharge lights up the cloud.

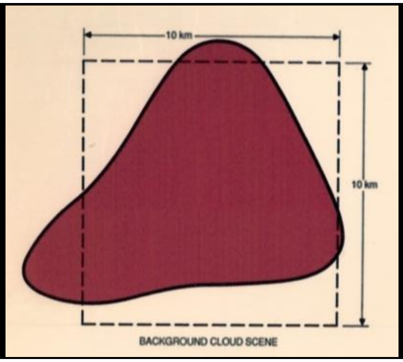
***Daytime Challenge:*** During day, sunlight reflected from cloud top dominates the lightning signal. Daytime lightning detection drove the design.

***Solution:*** Special techniques are applied to extract the weak, transient lightning signal from the bright, background signal.


***Spatial***

**Optimal sampling of lightning scene relative to back-ground scene.**

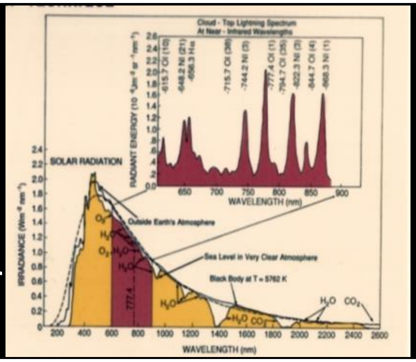
**Pixel field-of-view 4-10 km.**




***Spectral***

**Optimal sampling of lightning signal relative to back-ground signal.**

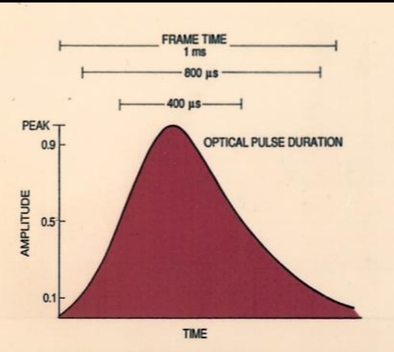
**LIS uses 1nm filter at 777.4 nm.**




***Temporal***

**Optimal sampling of lightning pulse relative to back-ground signal .**

**LIS uses 2 ms frame rate.**

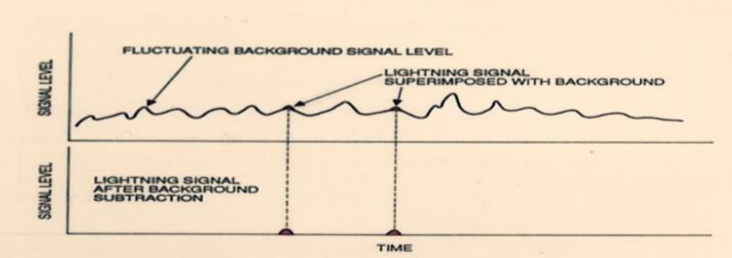


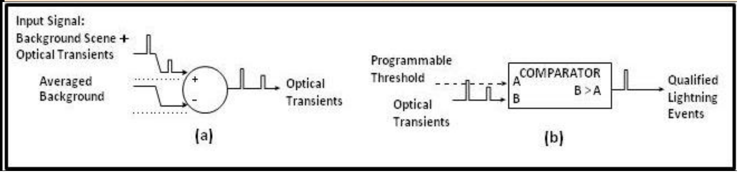

- *Even with spatial, spectral and temporal filters, background can exceed lightning signal by 100 to 1 at the focal plane.*
- *The final step is a frame-by-frame background subtraction to produce a lightning only signal*
- *Filtering results in $10^5$ reduction in data rate requirements while maintaining high detection efficiency for lightning .*

***Background Subtraction***

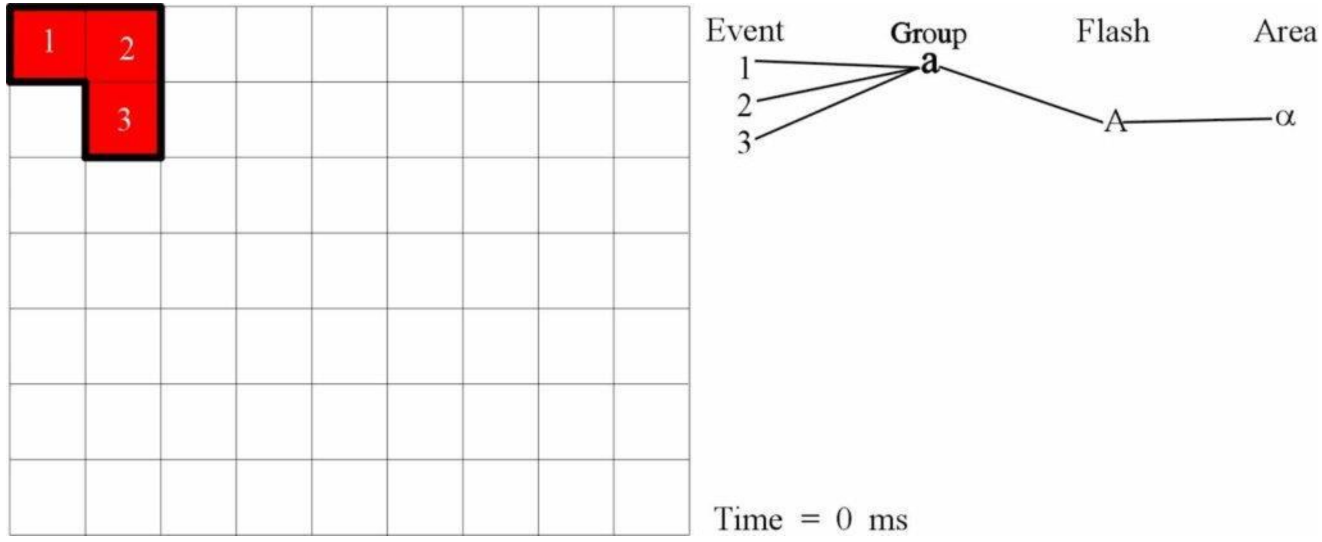
**Optimal subtraction of background signal levels at each pixel.**

**Transient events selected for processing.**

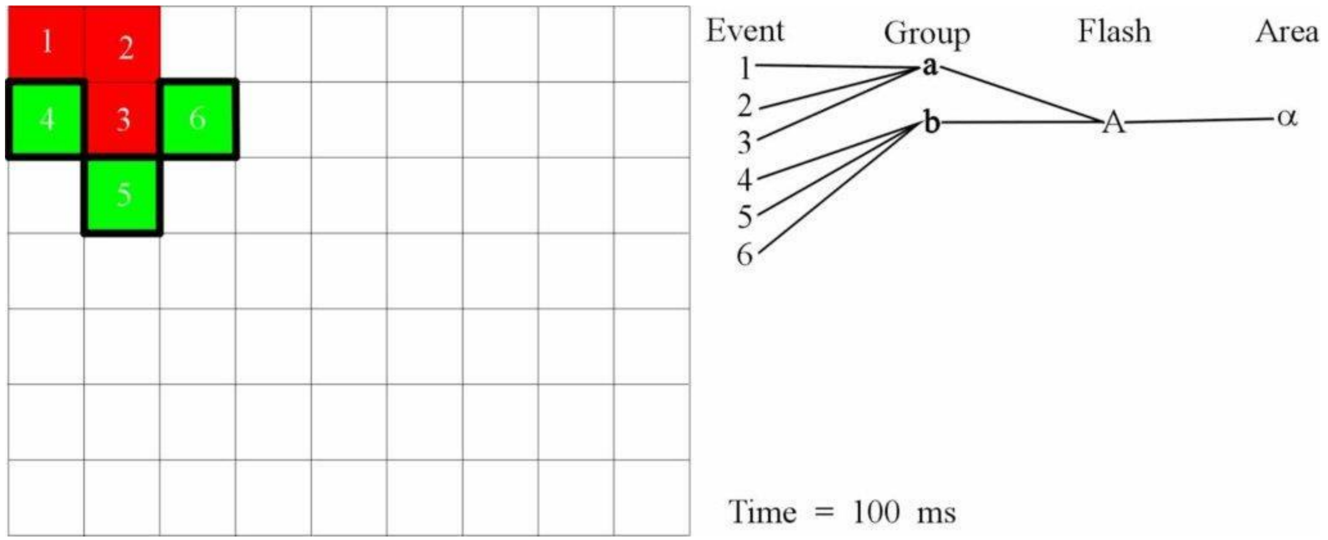


# Events Clustered to Flashes

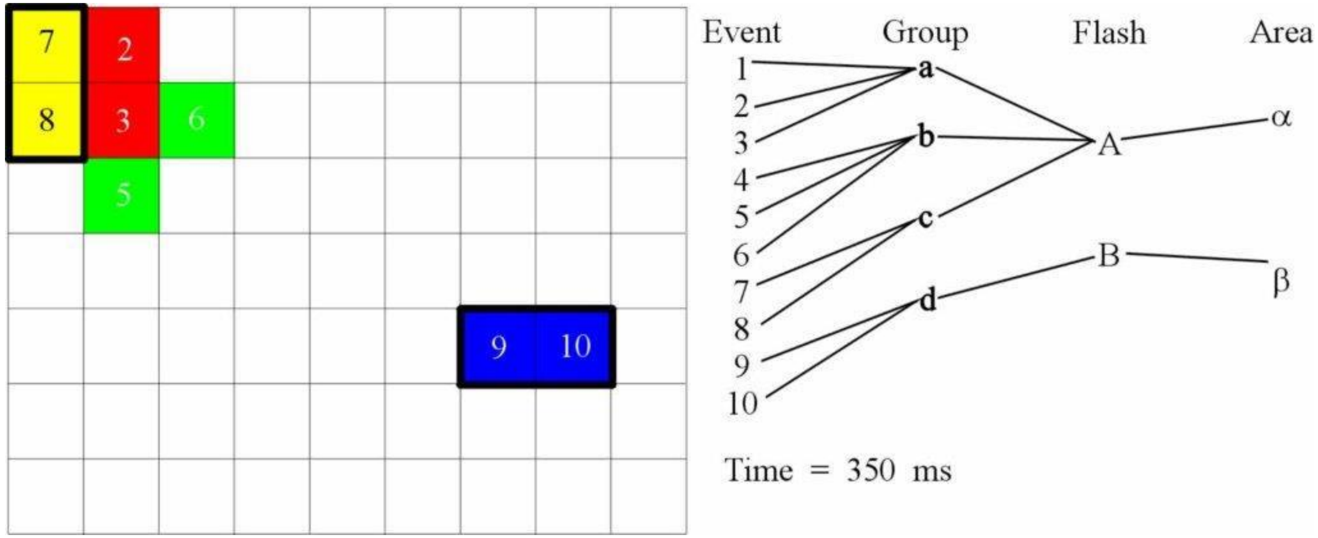



**Groups - Events that occur at same frame time in adjacent pixels**




**Flashes – Groups that occur close together in space and time**

# Events Clustered to Flashes (cont'd)




**A flash is ended when no nearby groups occur for 1/3 s.**

**GLM products – Geolocated (latitude, longitude), calibrated (i.e., radiant energy) events, groups , and flashes**

**Event geolocation – pixel latitude, longitude adjusted to specified cloud top height**
**Group geolocation – Radiance weighted mean event location**
**Flash geolocation – Radiance weighted mean group location**

# Why are Laser Beacons Beneficial?

- The GLM’s lightning detections must be navigated to 140 $\mu$rad (3$\sigma$) to provide geographically accurate severe weather warnings.
- The GLM’s error budget allocation is 112 $\mu$rad (3$\sigma$).
- The primary image navigation with respect to land features in the background Earth imagery is only useable from ~1000-1400 hours satellite time
- Navigation is extrapolated for entire day assuming GLM’s FOV is fixed with respect to GOES-16’s attitude reference from startrackers
- Thermal gradients can change the boresight between the GLM & the startrackers.  They are most severe at night when the satellite’s nadir surface is sunlit.
- The GLM’s wide-FOV lens assembly contains a large number of refractive elements. Misalignments among them can change boresight, focus & plate scale.  Radiation can change indices of refraction over the lifetime of the mission.
- Ground and space based observations of lightning are not necessarily co-located
- The beacon measurements provide unambiguous control points throughout the diurnal cycle that can be used to verify the image navigation algorithm and the GLM optical model or, if necessary, modify them.

# Laser Requirements

| Parameter | Requirement | Rationale |
|---|---|---|
| Wavelength ($\lambda$) | 777.2 ± 0.3 nm | GLM's central $\lambda$ at ~6.4$^o$ field angle |
| Pulse Repetition Frequency (PRF) | 50 Hz | Min PRF > 3 Hz Coherency filter<br>Max ~ 100-200 Hz for threshold relaxation |
| Pulse Duration ($\tau$) | 1.5 msec | Maximize power from CW laser & minimize frame splitting (1.8 msec exposures) |
| Received energy/pulse | > 50,000 photo-e's<br>< 1,500,000 photo-e's | Exceed threshold by ~10x to permit centroiding<br>Prevent saturation |
| Mode/ polarization | Mostly TEM00<br>Polarization not critical | Maximize received energy |

# GLM Beacons use MOBLAS Satellite Laser Ranging (SRL) Facilities

Beacons share existing MOBLAS pointing & tracking systems, and co-boresighted radar with shutter (Facilitates GSFC Code 350, FAA & LCH safety approval)

MOBLAS sites at Greenbelt, MD & Monument Peak, CA provide a long baseline within the GLM's FOV for GOES-16 & 17 during PLT (89.5$^{o}$ W) & for GOES-16 operating as GOES-E (75.2$^{o}$ W)

Laser beacon pulses transmits ~1.5 ms pulses @ 50 Hz & 777.2 nm (optimized for field angles)

Identical detection & processing for natural lightning & beacon pulses

No operational accommodation required for satellite nor interference with other instruments


**MOBLAS Station (above)**
Laser located inside station laser room & fiber coupled to telescope (important for safety, T & $\lambda$ control)

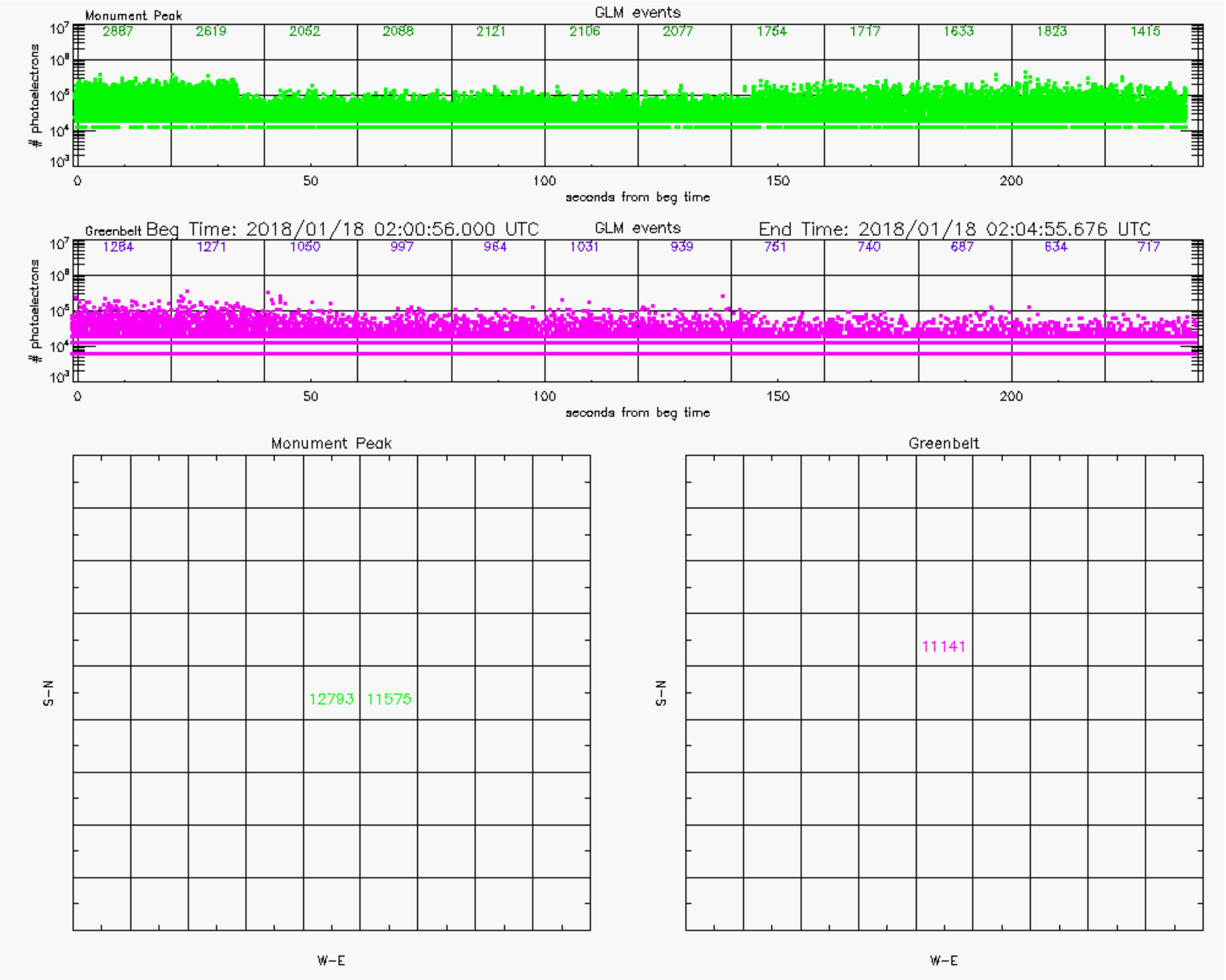
# GLM Beacons use MOBLAS Satellite Laser Ranging (SRL) Facilities

The piggybacked beacon telescope-fiber optics assembly on top of the NASA SLR telescope at the MOBLAS facility.

- Advantages of MOBLAS Laser Facilities:
  - Already staffed
  - Staff trained in satellite pointing using ephemeris data
  - Ability to perform GLM beacon operations along with normal SLR operations
  - Cost effective
  - Greenbelt, MD (MOBLAS 7)
  - Monument Peak, CA (MOBLAS 4)

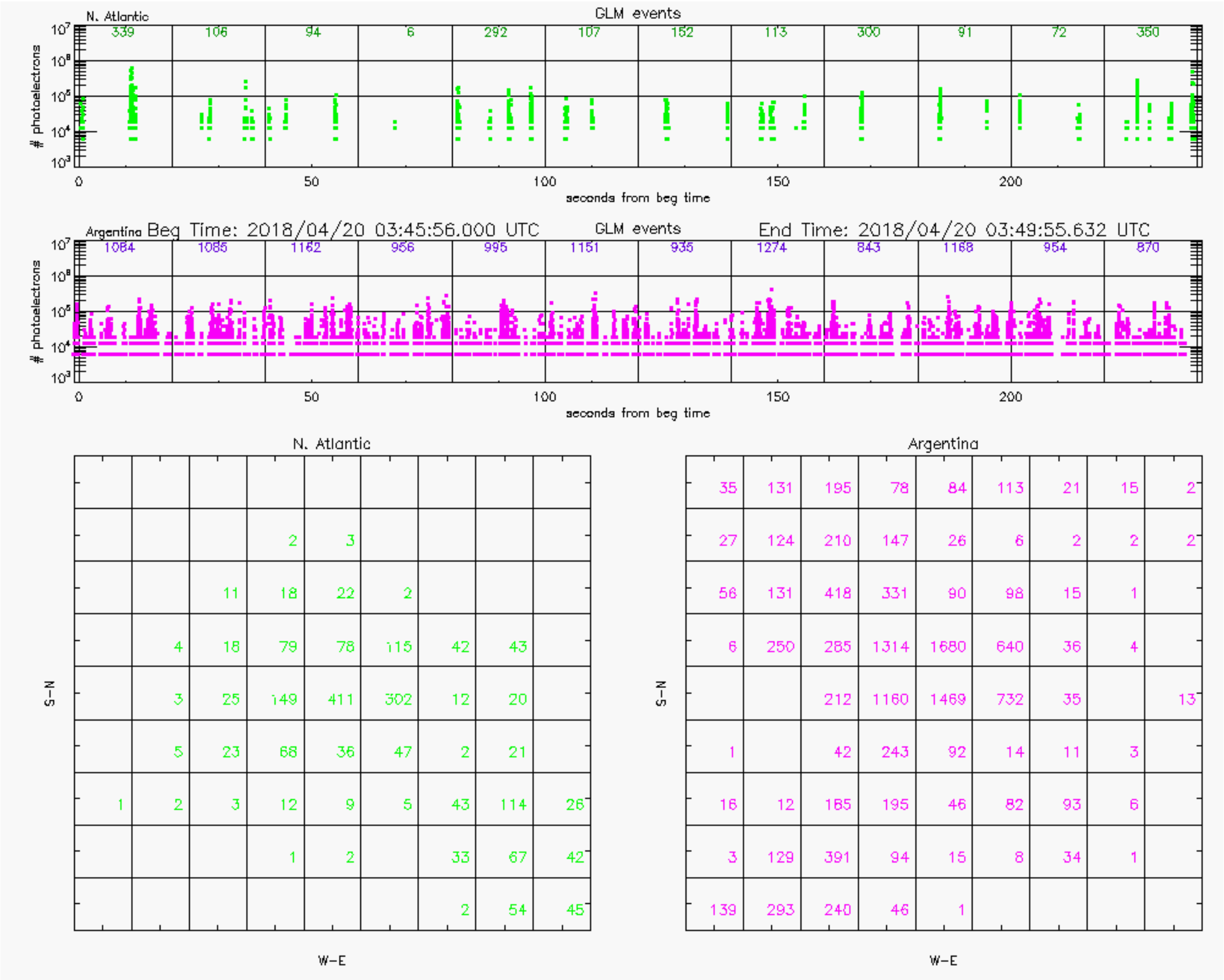
# Laser Beacon Web Page

- GLM Laser Beacon Operations
  - Need ability to monitor GLM activity at laser beacon sites
  - Near Real time web display was developed
  - GLM L2 data obtained via NOAA PDA (Product Distribution and Access)
  - Display latency of 1-2 minutes




These GOES-16 data are preliminary, non-operational data and are undergoing testing. Users bear all responsibility for inspecting the data prior to use and for the manner in which the data are utilized.

# Laser Beacon Web Page: Real Lightning Example

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# Laser Beacon Test Procedure

- The satellite ephemeris was obtained weekly from NOAA
  - Used to determine pointing angles
- Schedule dates 1-2 weeks in advance
- Notify NOAA so user notifications can be sent out
- Monitor weather conditions at sites
- Morning of test confirm go/no go based on:
  - Weather (clouds or high winds)
  - Personnel
  - Data availability
- Start web tool for monitoring test
  - Hosted on the GOES-R Field campaign web site

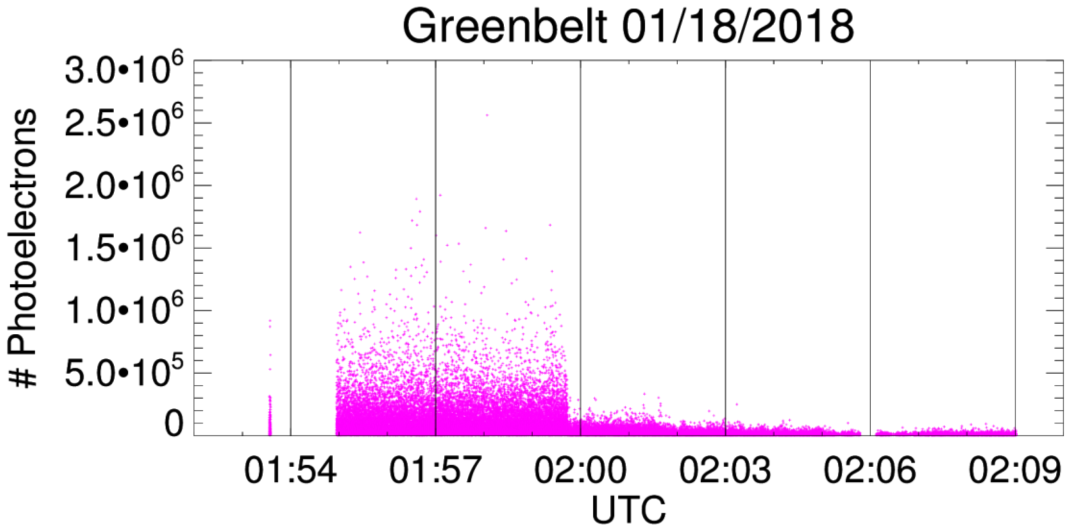
# Laser Operations

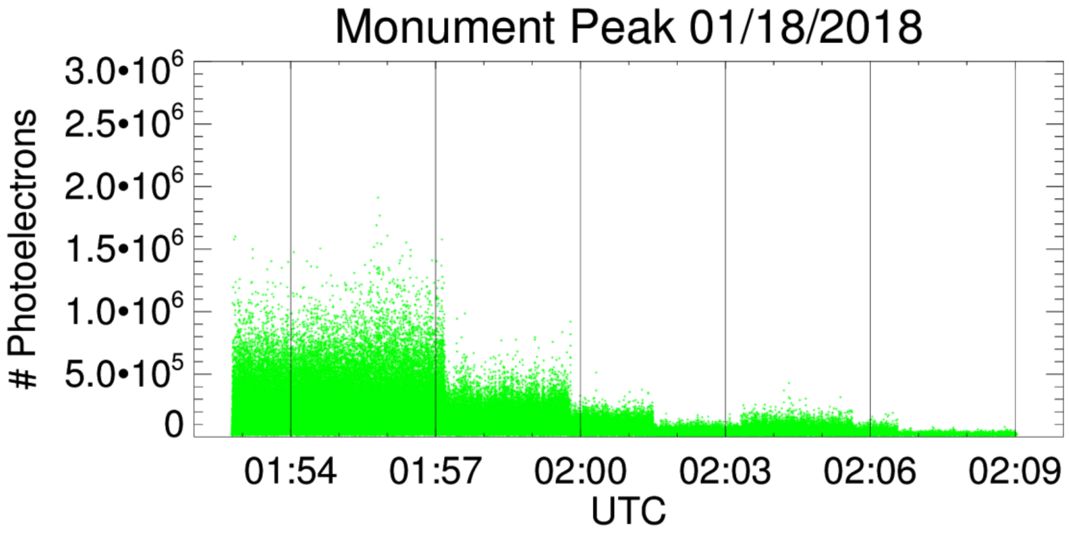
| Date | Time (UTC) | Location<br>GB-Greenbelt<br>MP-Monument Pk | Notes |
|---|---|---|---|
| April 19, 2017 | 0152-0352 | GB | |
| April 29, 2017 | 0055-0200 | GB | |
| May 3, 2017 | 1720-1850 | GB | dither |
| May 8, 2017 | 1730-1840 | GB | |
| June 9, 2017 | 1645-1710 | GB | |
| June 11, 2017 | 0300-0340 | GB | |
| June 13, 2017 | 1700-1712 | GB | dither |
| June 24, 2017 | 0420-0510 | MP | |
| June 28, 2017 | 1750-1754 | GB | Very few events |
| July 13, 2017 | 0339-0715 | GB & MP | |
| Aug 10, 2017 | 0225-0323<br>1440-1552 | GB & MP<br>GB & MP | Night<br>Day |
| Sep 5, 2017 | 1405-1455 | GB & MP | |

# Laser Operations (continued)

| Date | Time (UTC) | Location GB-Greenbelt MP-Monument Pk | Notes |
|---|---|---|---|
| Sep 21, 2017 | 1450-1655<br>1850-1830 | GB & MP<br>GB & MP | |
| Oct 2-3, 2017 | 1020/2-1409/3 | GB & MP | 24 hr test (hourly obs) |
| Nov 28, 2017 | 0340-0425 | GB | |
| Nov 29, 2017 | 0250-0320<br>2149-2215 | GB & MP<br>GB & MP | |
| Nov 30, 2017 | 0350-0415 | GB & MP | |
| Dec 19, 2017 | 2115-2130<br>2200-2240 | MP<br>GB & MP | At 75.2° W |
| Dec 20 , 2017 | 0010-0045<br>0155-0225 | GB & MP<br>GB & MP | |
| Jan 5, 2018 | 0018-0040<br>2250-2328 | GB<br>GB & MP | |
| Jan 6, 2018 | 0210-0240 | GB & MP | |
| Jan 17, 2018 | 2225-2255 | MP | |
| Jan 18, 2018 | 0150-0210<br>0445-0515 | GB & MP<br>GB & MP | |

# Results: Time Series

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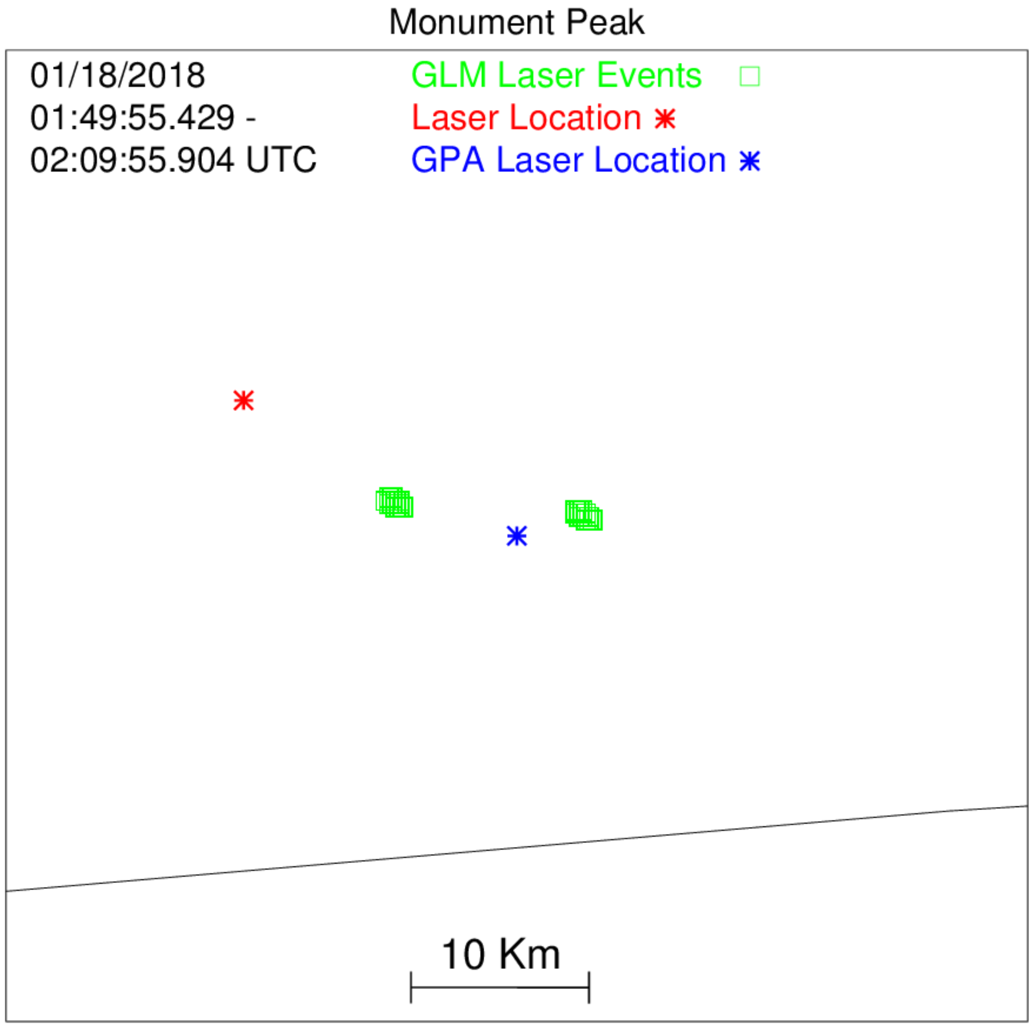
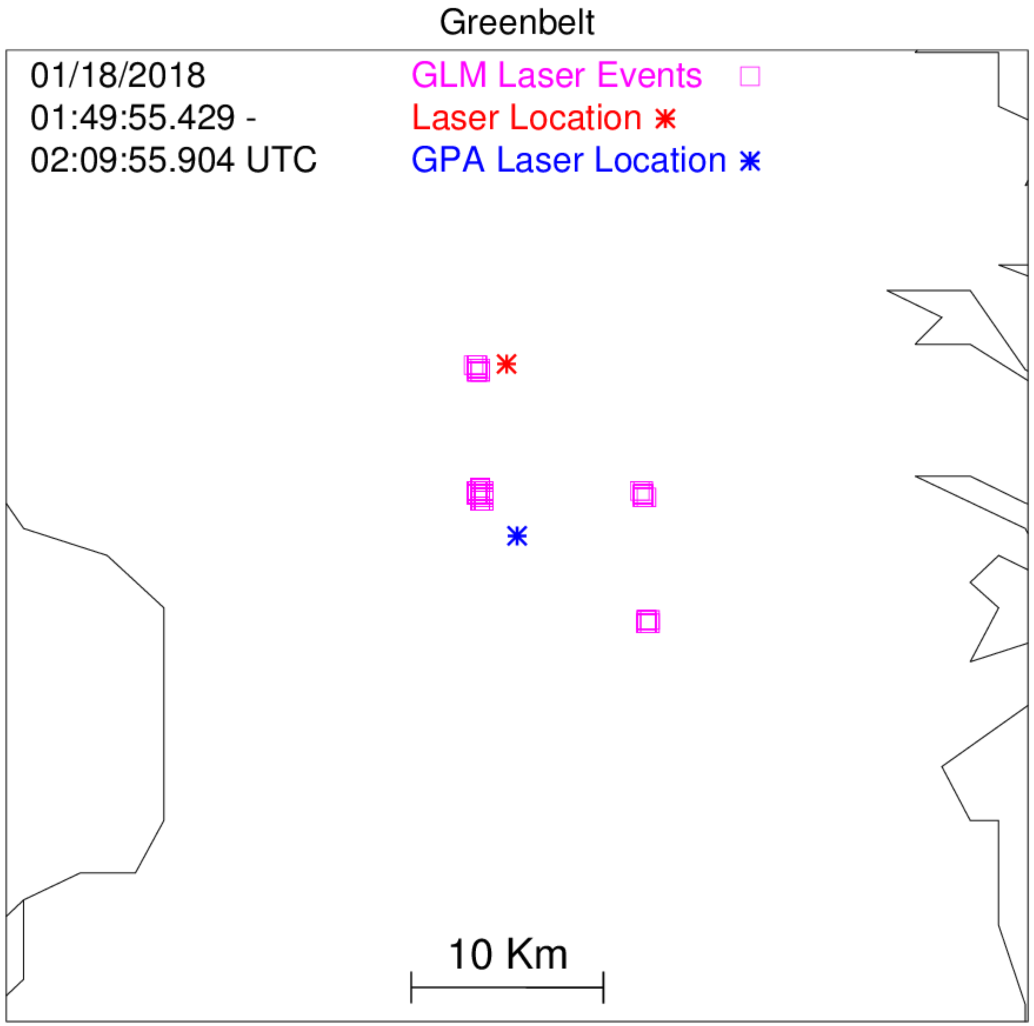
# Results: Events

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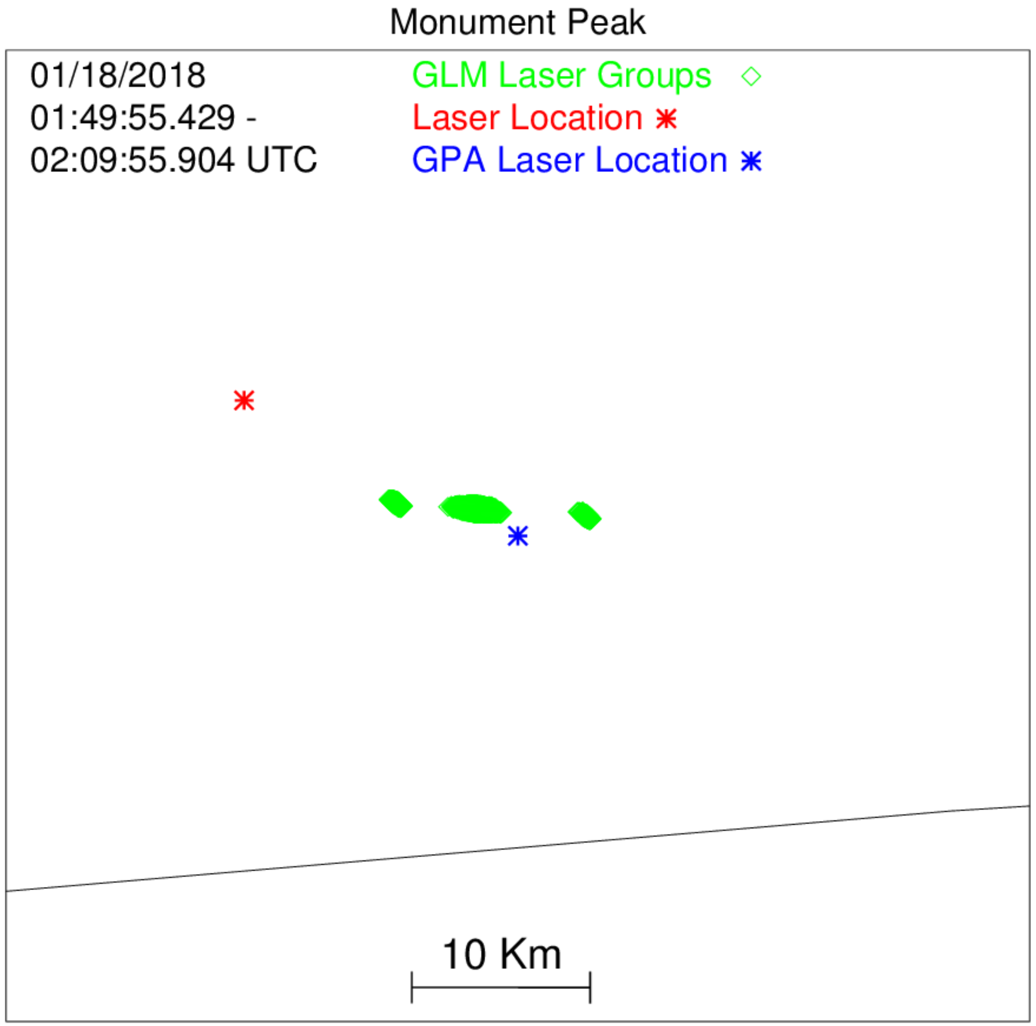
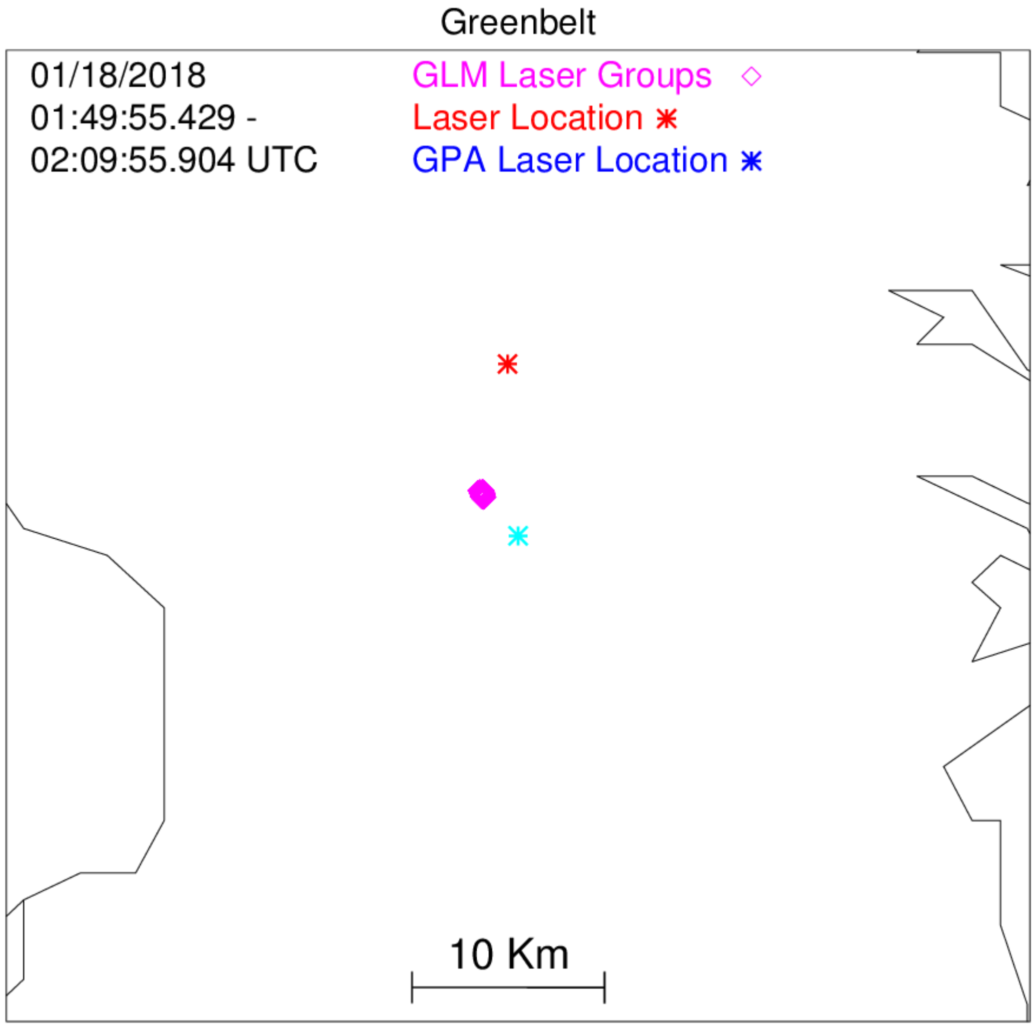
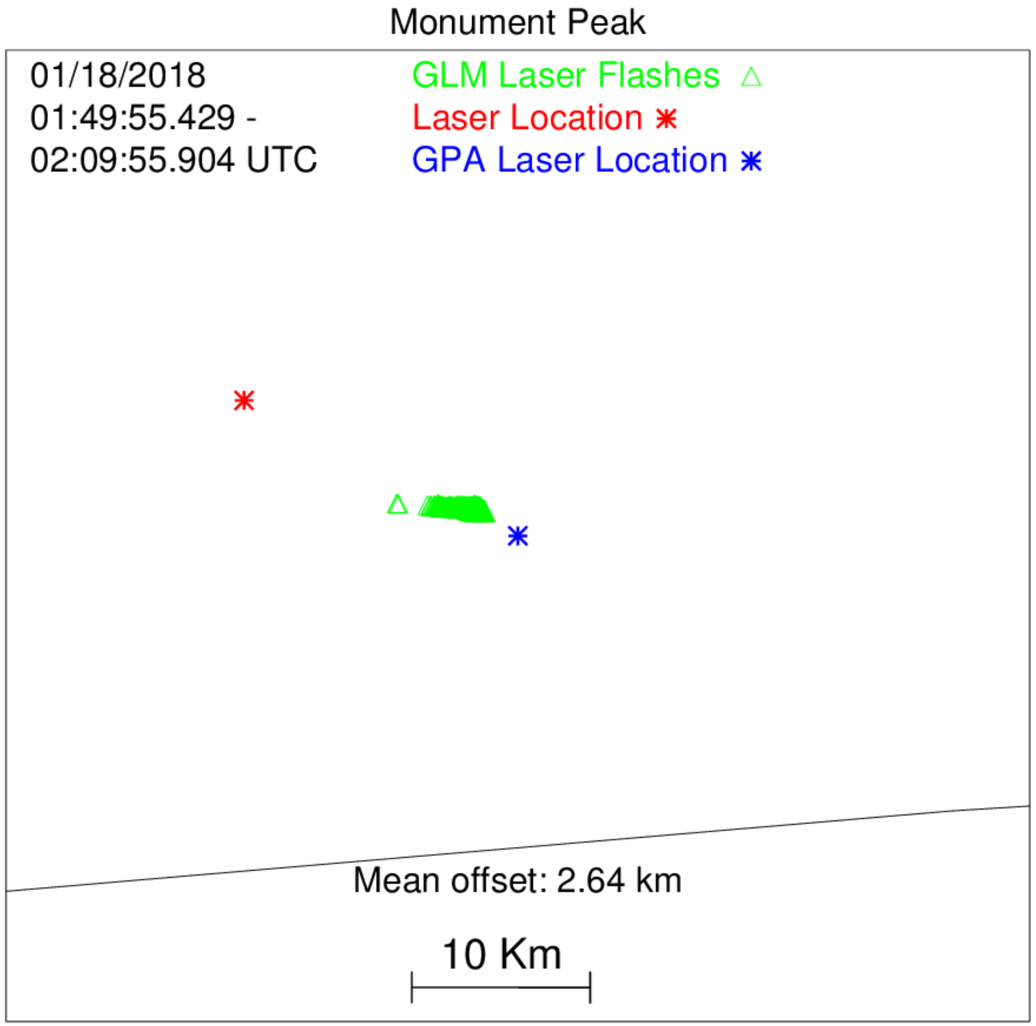
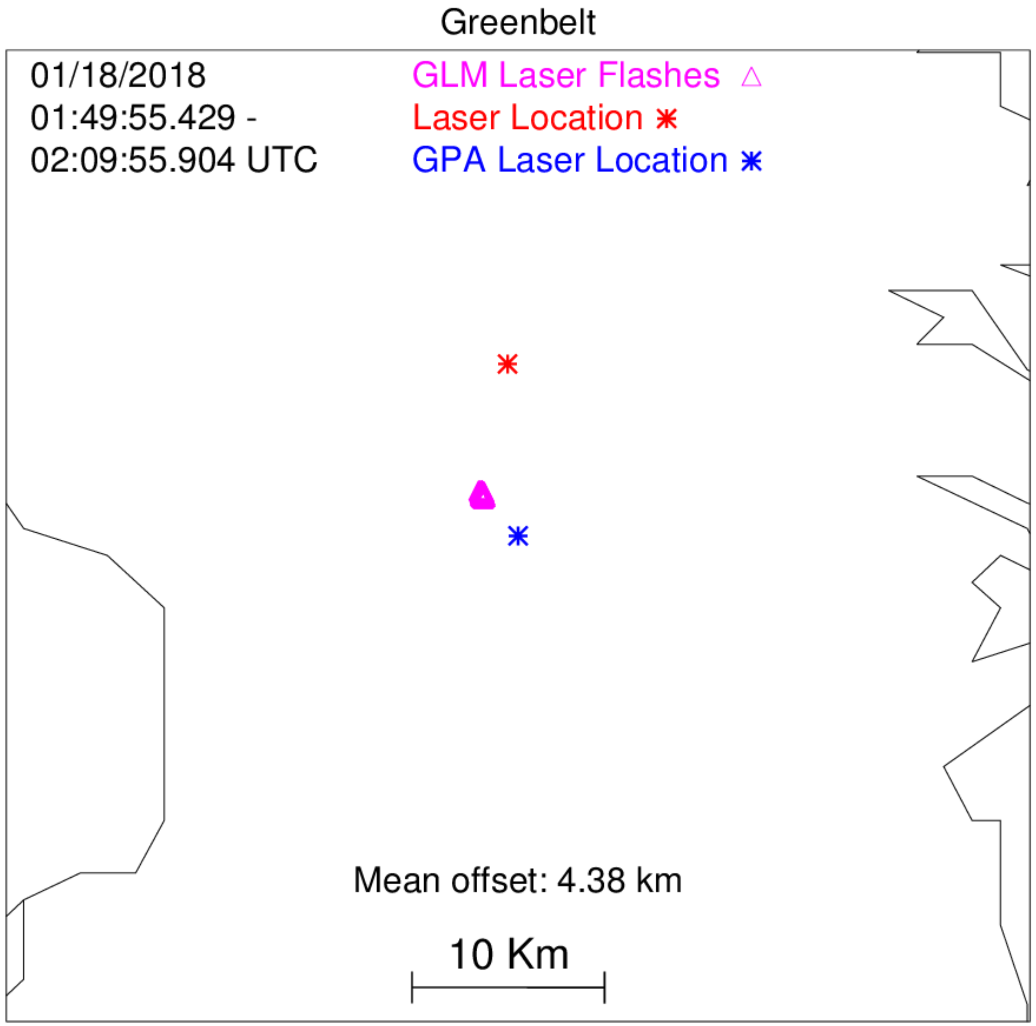
# Results: Groups



# Results: Flashes

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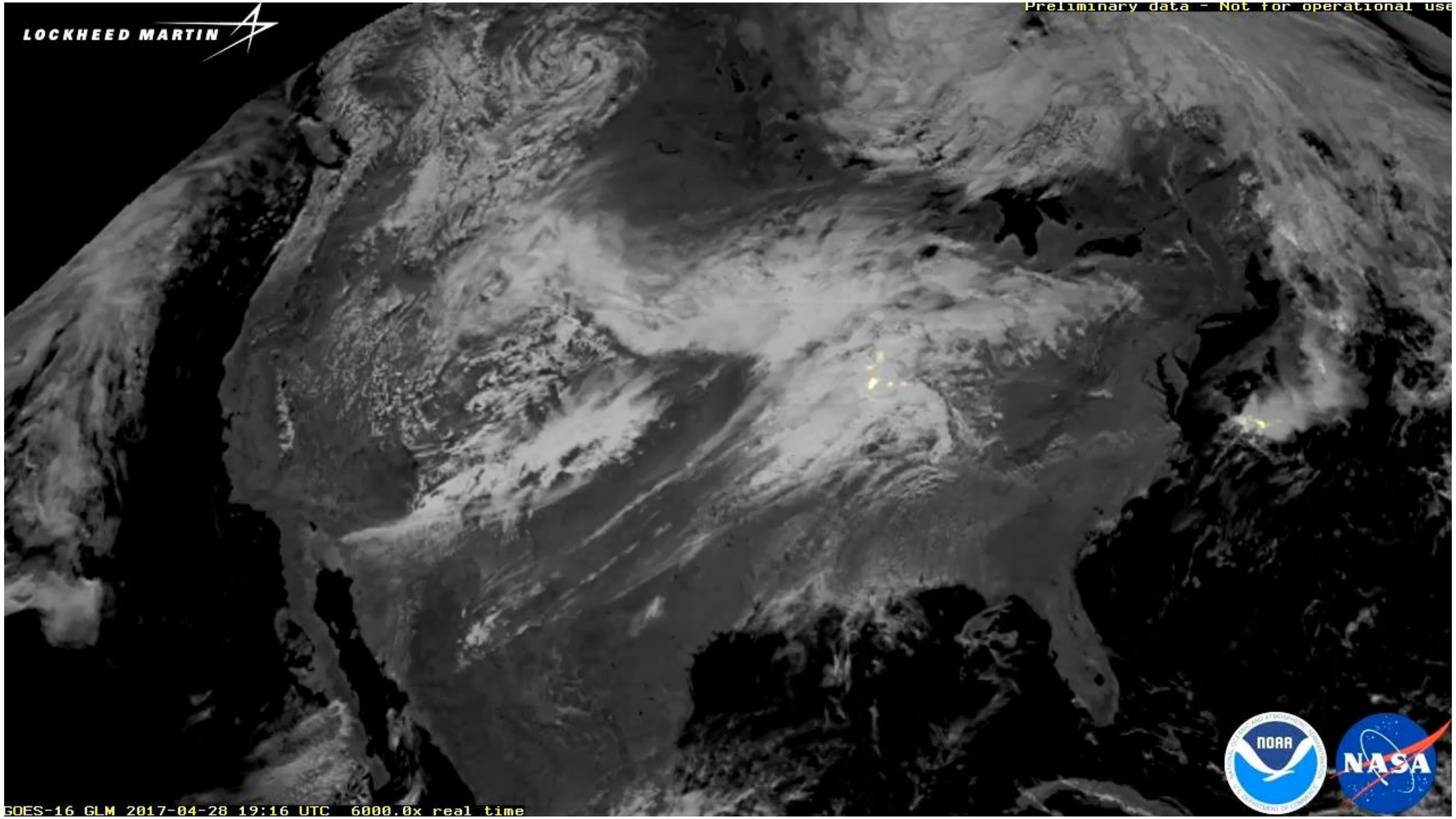
# Summary and Conclusions

- Demonstrated laser signal can be detected by GLM
- The laser signal detected by GLM passes through the GPA as lightning
- Developed a methodology for real time monitoring of GLM laser lightning
- Verified that the GLM “lightning” flashes were within 5 km
- The offset was also less than 5 km at 0500 UTC 01/18/2018 laser beacon period
- Laser operations now underway for GOES-17
- Further analysis of GOES-16 and GOES-17 datasets

# GLM backgrounds and lightning with laser beacon signal




https://www.youtube.com/watch?v=Uf9C-yr9iaA

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Thanks

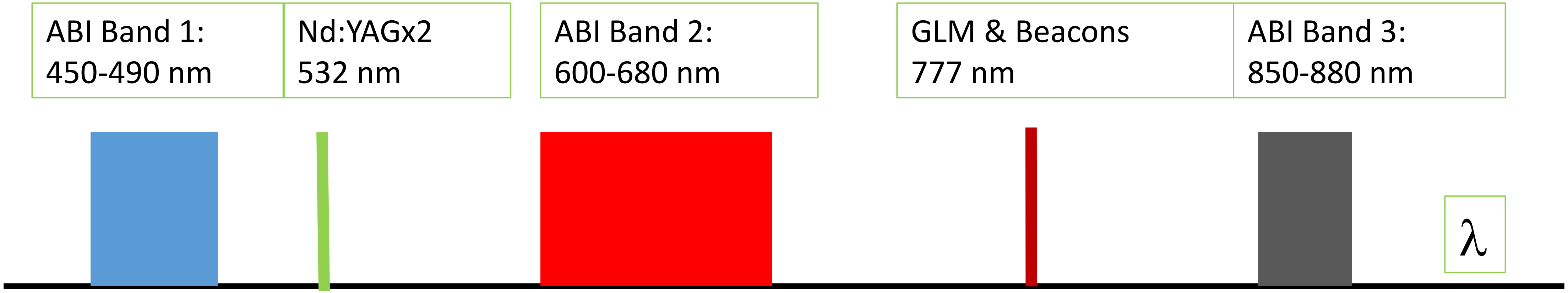
# Back-up Charts

# No Plausible Damage to the GLM or the ABI

Both GLM and ABI required to survive direct Sun in the FOV for > 2 min

Worst-case laser illumination of GOES-R (requiring major errors by beacon operators) won’t damage the GLM or the ABI

1. GLM laser beacon operated in CW mode:
   890x weaker than direct sunlight in a single pixel
2. Wrong laser: Nd:YAGx2 @ 532 nm:
   Not focused on ABI’s FPA (Blocked by spectral filters)



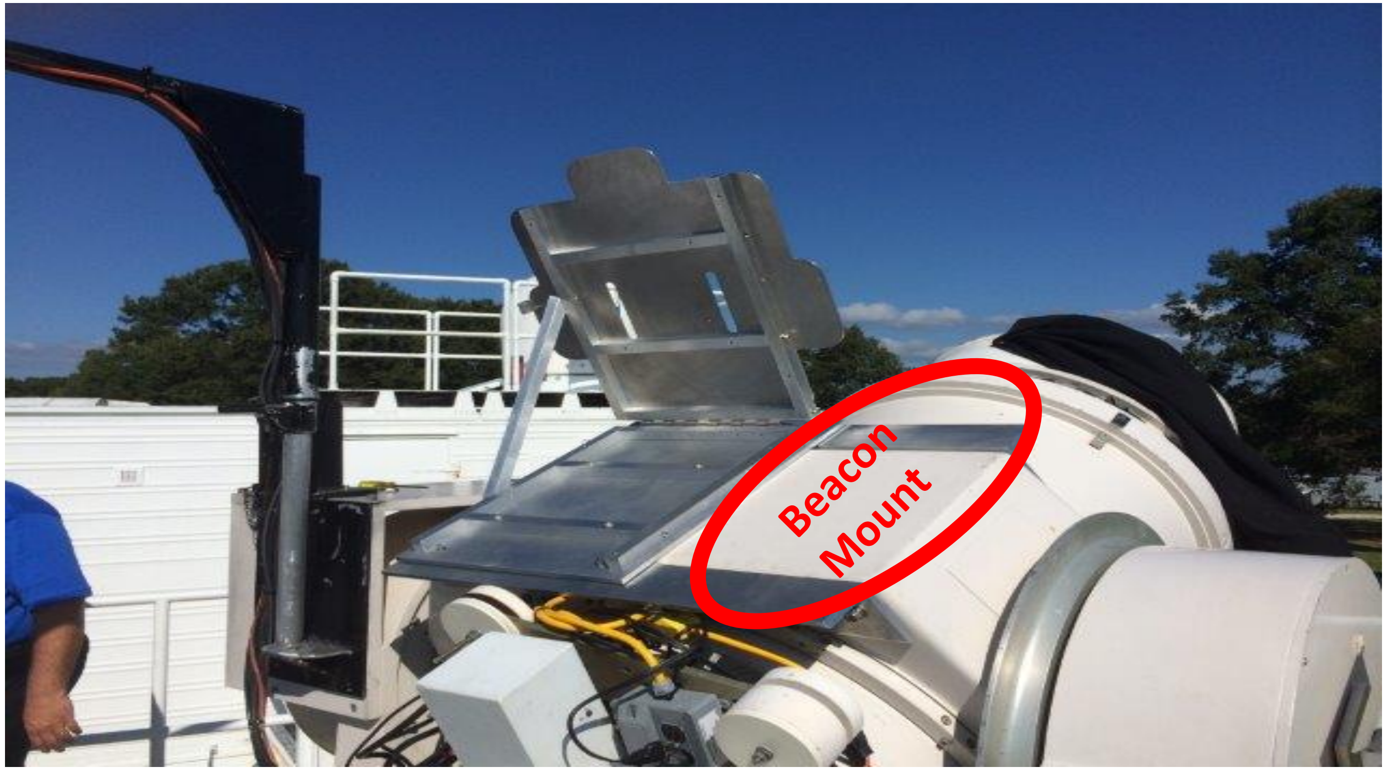
# Beacon parameters for GOES-E

| Parameter | GSFC to GOES-E | Mon. Pk. To GOES-E |
|---|---|---|
| Beacon Azimuth | 177.09° | 121.58° |
| Beacon Elevation | 44.81° | 31.64° |
| Range | 37,422 km | 38,466 km |
| GLM E/W field angle | 0.24° W | 5.31° W |
| GLM N/S field angle | 6.13° N | 5.16° N |
| GLM E/W pixel pitch | 30 μm | 24 μm |
| GLM N/S pixel pitch | 22 μm | 24 μm |

# Beacon Parameters for GOES-W @ 137°W (GSFC lies outside the GLM's FOV)

| Parameter | Mon. Pk./ GOES-W | Tahiti/ GOES-W | Mt. Haleakala/ GOES-W |
|---|---|---|---|
| **Beacon Azimuth** | 214.68° | 36.55° | 135.31° |
| **Beacon Elevation** | 45.79° | 64.81° | 57.34° |
| **Range** | 37,355 km | 36,307 km | 36,652 km |
| **GLM E/W field angle** | 2.90° E | 2.10° W | 3.09° W |
| **GLM N/S field angle** | 5.30° N | 3.02° S | 3.51° N |
| **GLM E/W pixel pitch** | 30 $\mu$m | 30 $\mu$m | 30 $\mu$m |
| **GLM N/S pixel pitch** | 24 $\mu$m | 30 $\mu$m | 30 $\mu$m |

# Beacon Telescope Mount

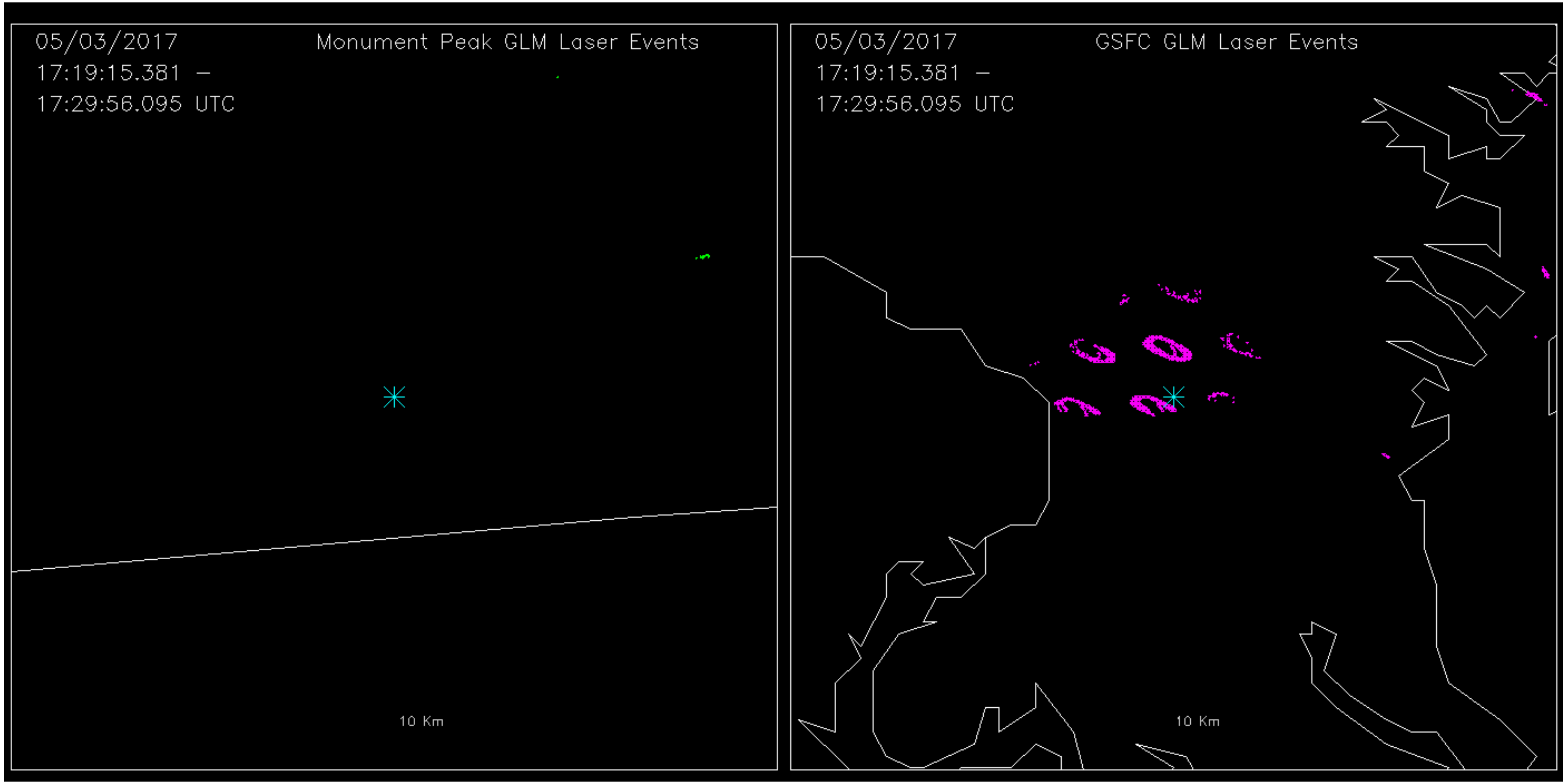



MOBLAS transmitters, optimized for Nd:YAGx2, transmit poorly @ 777.4 nm

Beacon telescopes "piggybacked" on MOBLAS telescopes uses their pointing system, co-boresighted radar, power, & enclosure

Inexpensive COTS telescopes have good transmission @ 777.4 nm

# Dither Events



# Results: Time Series